Proton Radiography

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Introduction

Protons can be used to probe with high spatial and temporal resolution the interior structure of systems that are static, imploding, or exploding. Protons have already been used to image thin systems, but the technique was limited by the image blurring caused in the object by the multiple scattering of the protons. The new development coming out of Physics Division is the introduction of a magnetic-lens system to remove much of this blur. Also, we are extending this technique further to gain information on the material composition of the object being probed by allowing a second detection of the transmitted protons through a reduced aperture. Experiments have been performed at the Los Alamos Neutron Scattering Center (LANSCE) and the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory (BNL) to confirm many of the concepts of proton radiography. A three-year program has begun to demonstrate the capabilities of proton radiography as a tool for advanced hydrotesting of nuclear-weapons primaries using high-energy (50-GeV) protons. A program at LANSCE is starting, using 800-MeV protons as a research tool for Science-Based Stockpile Stewardship (SBSS), looking at shock-wave propagation in high-explosive (HE) systems.

The SBSS Program and the Stockpile Stewardship and Management Program were developed to assure the reliability and safety of the weapons in the enduring stockpile without the use of nuclear testing. Effects that will need to be addressed will arise due to aging of components, remanufacture of weapons and weapon components, or possible packaging changes. In the past, such effects often were assessed with nuclear testing. As part of this comprehensive program to understand the fundamental physics of a nuclear device through modeling and nonnuclear experiments, the integral performance of a nuclear assembly must be measured with substantially improved fidelity. An advanced radiographic capability is an essential component of this program, providing the ability to measure the integral performance of stockpiled primaries using inert materials and thereby derive nuclear performance information that previously could only be obtained from nuclear testing. Detailed data from these hydrodynamic experiments are the necessary starting points for modeling the explosion phase of the primary and thus for assessing the performance and safety of stockpiled primaries.

The primary is the most difficult component of a nuclear weapon to assess for reliability because changes, though small, have the potential to affect the boost process. Three of the most important parameters affecting primary boost and thus yield performance are the level of supercriticality produced by HE compression, the shape of the boost cavity, and mix within the cavity. For assessing nuclear safety in an accident, the integral of the level of supercriticality over of time must be determined. Hydrodynamic testing is the only available tool for measuring the integral performance of a primary up to the beginning of criticality. Currently, pin measurements (wherein electrical pins of varying lengths are arrayed inside of a primary or primary surrogate and are progressively shorted out as the primary implodes) and radiography of an imploded pit and cavity are used to constrain computational simulations from which nuclear performance and safety are calculated. In the absence of nuclear testing, it is essential that hydrotest capabilities be expanded to include experimental validation of calculated nuclear performance. A multiaxis (>2 axes), multipulse, radiographic system does not currently exist, and none is anticipated for the near future. The Advanced Hydrotest Facility (AHF) is being proposed to meet this challenge.

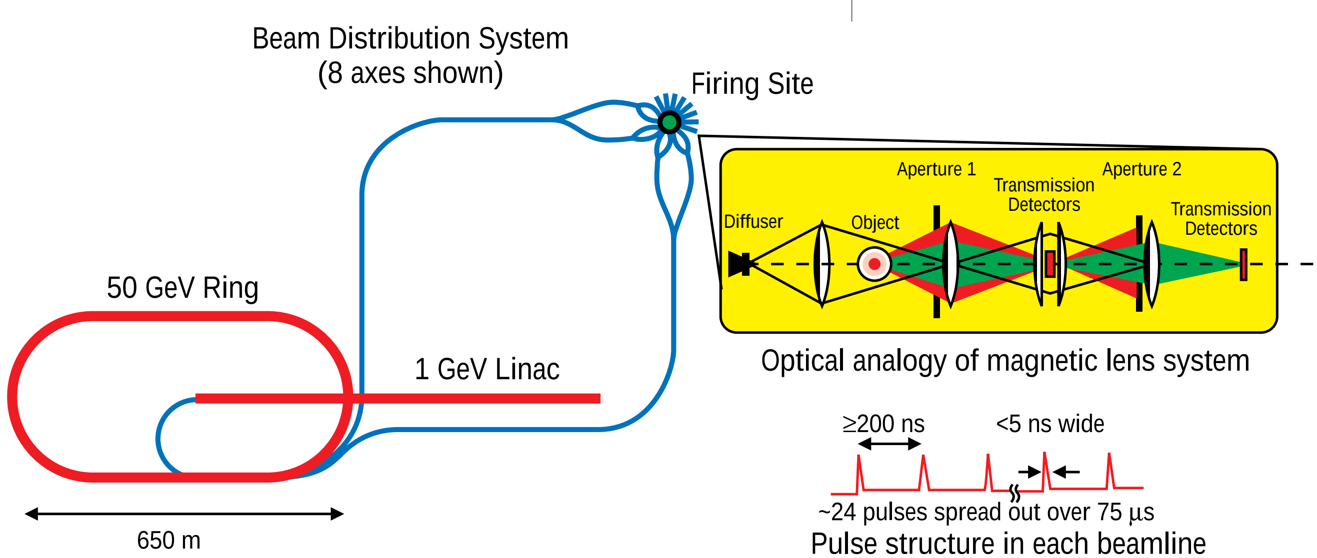
Hydrodynamic radiography refers to that technology used to view inside thick material objects (specifically the primaries of nuclear weapon assemblies) as they are undergoing implosion and compression because of the detonation of surrounding HE. The principal tool of hydrotesting is thick-object-penetrating radiography. The images obtained must be formed very quickly (in ~50 ns or less) to freeze the motion of the moving components and features and to avoid motion blur. The images are negatives, in that the information depicting the primary assembly's internal structure is obtained from the attenuation of the penetrating radiation. Current state-of-the-art facilities are PHERMEX at LANL and FXR at Lawrence Livermore National Laboratory (LLNL). Both are important elements of current stockpile maintenance, and efforts are continuing to upgrade their capabilities through double pulsing and enhanced detector capability. These two facilities will remain the prime radiographic facilities until the completion of the Dual Axis Radiographic Hydrotest (DARHT) facility in FY 1999 (for the first axis) and FY 2002 (for the second axis). DARHT will improve radiographic resolution and x-ray intensity (dose) and provide dual-axis tomographic data to evaluate asymmetries in primary assemblies. It will also provide improved data for the development of the analysis tools that will be needed for the proposed AHF. The AHF is proposed to provide improved understanding of three-dimensional effects associated with aging and weaponization features of weapons and to provide time-dependent, high-resolution measurements of pit density and gas-cavity configurations. It would expand multipulsed, multiaxis capabilities well beyond those being planned for DARHT.

An advanced radiographic capability will have to provide accurate information about densities and material positions, from which we can infer the degree of supercriticality, the shape of the boost cavity, and the mix that would be present in an actual imploding primary. Allowed manufacturing tolerances can cause an implosion to be three dimensional even in normal operation, and accidental detonations are almost always three dimensional. As a result, radiographs are needed from a number of directions (at least 4 and preferably 12) so that material densities can be reconstructed with accuracies sufficient to derive nuclear parameters. Also, since the implosion progresses with time, a temporal series of radiographs (5–10) is needed over a time period relevant to the processes being recorded. This time window may need to cover a period as long as the full implosion. Two radiation species are under consideration as possible advanced technologies for an AHF: multi-MeV x-rays and multi-GeV protons. The overall utility and performance of both types of radiation will be studied to select an optimal technology mix.

In x-ray radiography, a beam of energetic electrons is accelerated and then focused onto a dense, high-atomic-number material target, producing bremsstrahlung x-rays. The necessary penetrating dose requires many kiloamperes of electron beam current with >10 MeV of kinetic energy impinging on a converter target located about a meter from the hydrodynamic object. To resolve small feature-sizes within a weapon-primary assembly, the x-ray source must be a very small spot size (approaching a point source) thus requiring a very-small-diameter electron beam. There are two technology paths under consideration for x-ray hydrodynamic radiography: linear induction accelerators (LIAs) and inductive voltage adders (IVAs). The LIA approach uses a single high-voltage, high-transport-current (20- to 40-MeV, 1- to 6-kA), large accelerator producing a long-duration electron beam that is distributed via a kicker into many axes, each of which transports a shorter-duration beam to a bremsstrahlung converter. The IVA approach uses smaller medium-voltage, higher-current (12-MeV, 40-kA), individual accelerators to directly generate the short-duration pulses that are delivered to the bremsstrahlung converters.

In proton radiography, a high-energy beam of protons impinges directly on the object to be radiographed. There is no need for an equivalent bremsstrahlung converter since the proton beam directly illuminates the primary assembly. Unlike x-rays, protons undergo a large number of very forward-angle scatterings as they pass through the object and the exit window of the containment vessel. This introduces a blur to the image that is then removed, for the most part, by a magnetic lens system between the object and the detectors. The residual blurring can be further reduced by increasing the energy of the proton beam. For typical weapon-primary assemblies and containment-window thicknesses, this corresponds to proton beam energies near 50 GeV. The proton beam is produced in conventional accelerator architectures, including an injection linac and synchrotron ring. The inherent time structure of the acceleration process lends itself naturally to the variable pulse formats needed for advanced radiography. Each pulse in the ring is of short duration (less than 50 ns), with many pulses present in the ring. A kicker system is used to deliver the required pulse format, both the pulse spacing and the total duration of the pulse train. Each pulse can then be split into multiple pulses and delivered simultaneously to the object through multiple beamlines. The number of protons in a single pulse must be adequate to meet the density and field-of-view requirements. At the present time, it is estimated that 5×10^9 protons per pulse per axis are needed. With 10 axes, this would imply 5×10^{10} protons per pulse. Considerably more intensity is available with current technologies (over 10^{13} at the AGS at BNL and the proton storage ring [PSR] at LANSCE), so that higher fluxes are available if warranted by refinements in the radiographic requirements. Figure II-55 is a schematic of a proton-based AHF, showing the injection linac, 50-GeV ring, beam distribution system, firing point, and lens system.

Fig. II-55. Schematic of a proton-based Advanced Hydrotest Facility.



Proton Radiography

Proton radiography marks a sharp departure from flash x-ray technology, which has been the exclusive radiographic tool for stockpile support for more than thirty years. Here, the primary proton beam of a suitably high energy (near 50 GeV) is used to image the imploding object directly. Both the nuclear attenuation and the multiple scattering of the protons contain information on the distribution and composition of materials in the object. The principle virtues of protons are (1) the relatively long mean-free-paths of protons, well matched for the imaging of dense objects, (2) the maturity of proton-accelerator technology, which can accommodate the multiaxis, multipulse format required for an AHF, (3) lack of significant scattered background in the final image, (4) sensitivity to both material density and composition, (5) direct utilization of the proton beam as the radiographic probe, (6) high detection efficiency, (7) high reliability because the beam is coasting in the storage ring before the time of firing, and (8) the ability to easily deliver a test beam in advance of firing. The capabilities of proton radiography will likely exceed the current AHF requirements in several categories, providing a great deal of flexibility for enhancing future AHF capabilities. What is mostly wanting for protons at this time is radiographic experience with weapons-relevant dynamic systems. Common to both protons and x-rays is the need for fast, large-format, pixelated detectors; simulation capabilities to better understand the performance of the full radiographic system; and the facility issues related to practical problems of actually making the required measurements.

800-MeV SBSS Research Tool

We can use 800-MeV protons to radiograph dynamic systems with areal densities up to 20 g/cm^2 for low-Z materials using intensities available from the LANSCE linac, typically 2×10^9 protons per 40-ns pulse. This capability is well suited for studies of HE shock propagation. A dynamic radiographic system has been installed in Line B at LANSCE, including a beam transport system, imaging lens, multiframe detection system, and containment system. LLNL is collaborating on this project and has been involved in simulations and detector development. The first experiments have looked at shock propagation in HE hemispheres and have also explored cylindrical geometries. The major issues to be addressed are how the shock from the detonator propagates through the HE and which parts of the HE react as a function of HE properties and temperature.

Figure II-56 shows the measured spatial resolution of the LANSCE apparatus. A metal "comb" with 1- and 2-mm-spaced slots was radiographed. The fitted position resolution was found to be better than 0.5 mm full width at half maximum (FWHM).

Fig. II-56. Measured resolution of the LANSCE proton-radiography apparatus.

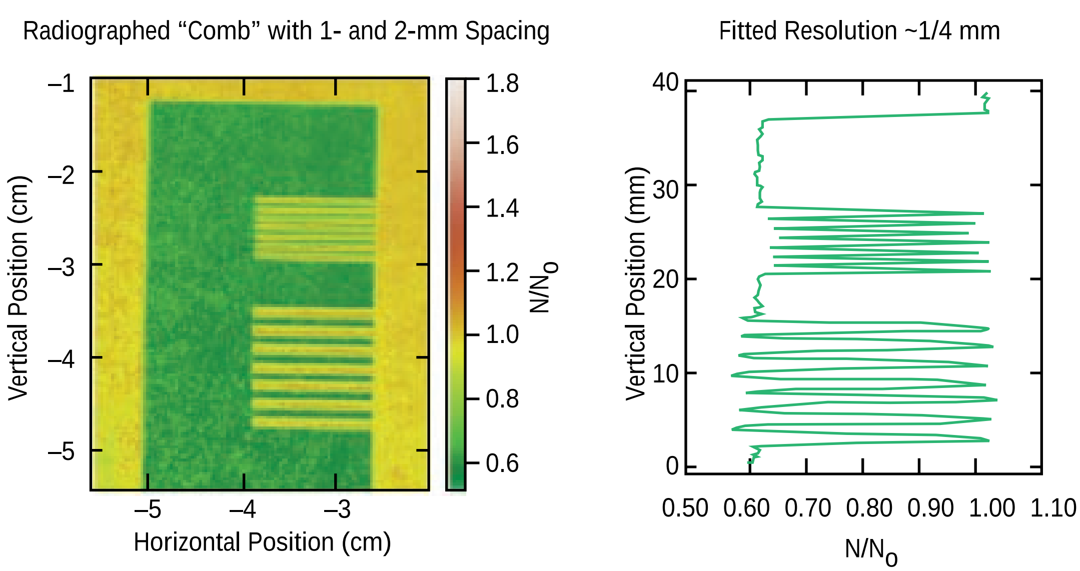


Figure II-57 shows a detonation wave at four different times in an HE assembly. The assembly consists of two embedded hemispheres of high explosives with a detonator. The inner shell is normal HE and the outer shell is insensitive high explosive (IHE). The diameter of the outer shell is approximately 5.7 cm, with a total HE mass of 92 g. The dotted line represents the edge of the unreacted HE. The propagation of the detonation wave is clearly evident in the radiographs as it propagates from the detonator to the outer surface of the IHE. What is shown is actually the ratio of the dynamic radiograph to a radiograph of the object taken before detonation. This enhances the changes visible in the dynamic radiograph. The images were recorded on a phosphor image plate that allows for one image per shot. An active camera system has now been installed, which is capable of taking up to six frames during the time of a single HE explosion.

The limitations to thin, low-Z systems at 800 MeV come primarily from multiple scattering within the object and aberrations in the lens system. Both of these effects become less important as the beam energy goes up, so these are not basic limitations for weapons-geometry hydrotests. A beam energy of approximately 50 GeV would be adequate to achieve 1% density measurements on a 1-mm^2 pixel size, with submillimeter resolutions for thick, dense systems (several hundred g/cm^2).

It is possible to overcome some of the limitations at 800 MeV by reducing the aperture in the lens through which the transmission is measured. This reduces the effects of chromatic aberrations in the lens. However, this also reduces the transmitted intensity, and hence, the sensitivity of the measurement. By using the beam from the PSR at LANSCE, the initial intensity of the pulse can be increased by four orders of magnitude, since 2×10^{13} protons are stored in a PSR pulse. A

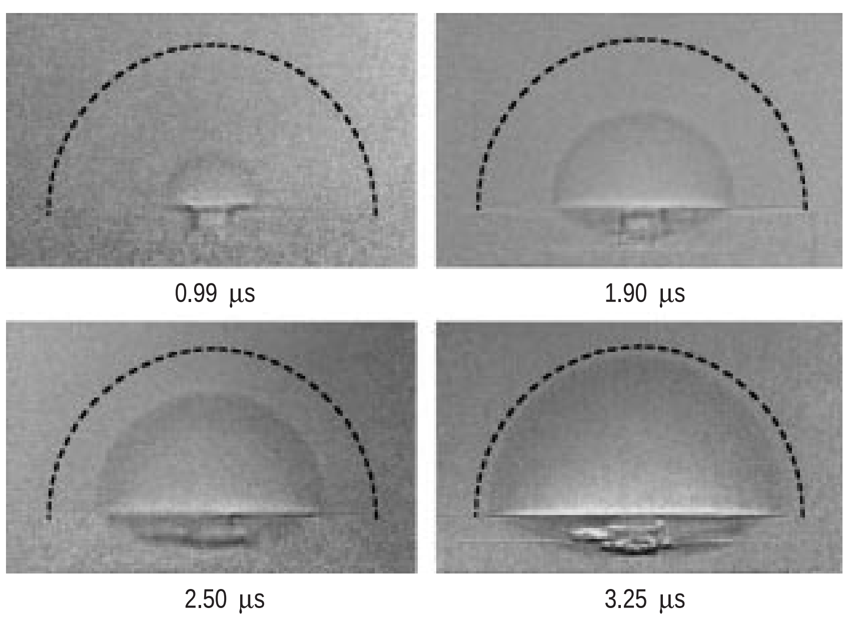


Fig. II-57. Proton radiographs of shock propagation at four different times in an HE assembly.

development has been recently completed where the PSR pulse was split into two pulses separated by 360 ns, each pulse being less than 50 ns wide. The PSR is being upgraded to store three pulses at full intensity. By using this splitting technique, 6 pulses could be extracted from the PSR and delivered to a firing site to radiograph thicker (100 g/cm^2) higher-Z dynamic systems. A study was recently completed that showed how to marry the higher-intensity 800-MeV proton radiography capability with neutron resonance spectroscopy, which can measure temperature and velocity in materials, in one facility at LANSCE.

Advanced Hydrotest Capability

Protons are one of three technology options being considered for an AHF. Recently, the three weapons program directors from LANL, LLNL, and Sandia National Laboratories (SNL) requested a technology development plan that would demonstrate over a three-year period the viability of the three technologies. LANL was designated the coordinating laboratory for protons, LLNL for LIAs, and SNL for IVAs. Technical Contracts, modeled after the Nova Technical Contracts for NIF, have been drafted that define the critical issues to be addressed, together with the tasks and goals, and Implementation Plans with cost and schedule information for accomplishing the Technical Contracts have been completed, as well as an additional contract covering physics requirements. Work began in FY97 toward these objectives. LLNL is now collaborating with LANL on proton radiography, and all planning is being done jointly with them.

The 3-year plan addresses the following critical issues for proton radiography:

- demonstration of proton radiography performance on a suitable array of test objects under conditions as near as possible to the anticipated design parameters of an AHF;
- development of instrumentation capable of meeting the AHF requirements for spatial and temporal resolutions and required pulse format;
- demonstration of a proton-accelerator concept capable of meeting AHF requirements;
- examination of the effects of the confinement system on resolution and of its interfacing to the lens system; and
- demonstration, in conjunction with the physics requirements modeling effort, that uncertainties in the radiographic image, after correction for known experimental effects, are consistent with criticality, cavity shape, and mix physics-data requirements.

One of the major experimental efforts of this plan is to construct a new beamline at the AGS at BNL to accept up to eight pulses of 25-GeV protons directly from the AGS at intensities typical of an AHF. This will allow tests of thick, weapons-geometry objects at near-AHF conditions. Previous experiments at the AGS used secondary beams of lower energy and intensity. These provided some of the early concept validation of proton radiography and have set the stage for this next step. Figure II-58 shows a proton radiograph of the French Test Object using 10-GeV protons at the AGS. The reconstructed densities and material boundaries are in good agreement with the known values. We plan to move the present proton-radiography experiments from Line B to the adjacent Line C, providing more space for multiple-lens configurations and larger containment vessels for larger HE charges. It is expected that this new area will be available for experiments in the FY98 run period at LANSCE.

Another major element of the program is development of high-resolution detection systems that are capable of multiple-frame recording. Since protons are charged, direct detection is possible. A prototype pixelated silicon array has been constructed, capable of buffering 1024 frames with 200-ns interfame separation. Electro-optic systems are also being developed. We anticipate that the testing of these systems will use the LANSCE beam and Line B apparatus over the next three years. This same setup can be used to evaluate and test new containment designs that would be applicable to the AHF requirements. Data from the Line B/C experiments will be used to benchmark and validate many aspects of the simulation and analysis effort for AHF development. At the end of this research and development program, proton radiography will be in a position to be evaluated, together with the other two technologies, as a viable tool for advanced radiography.

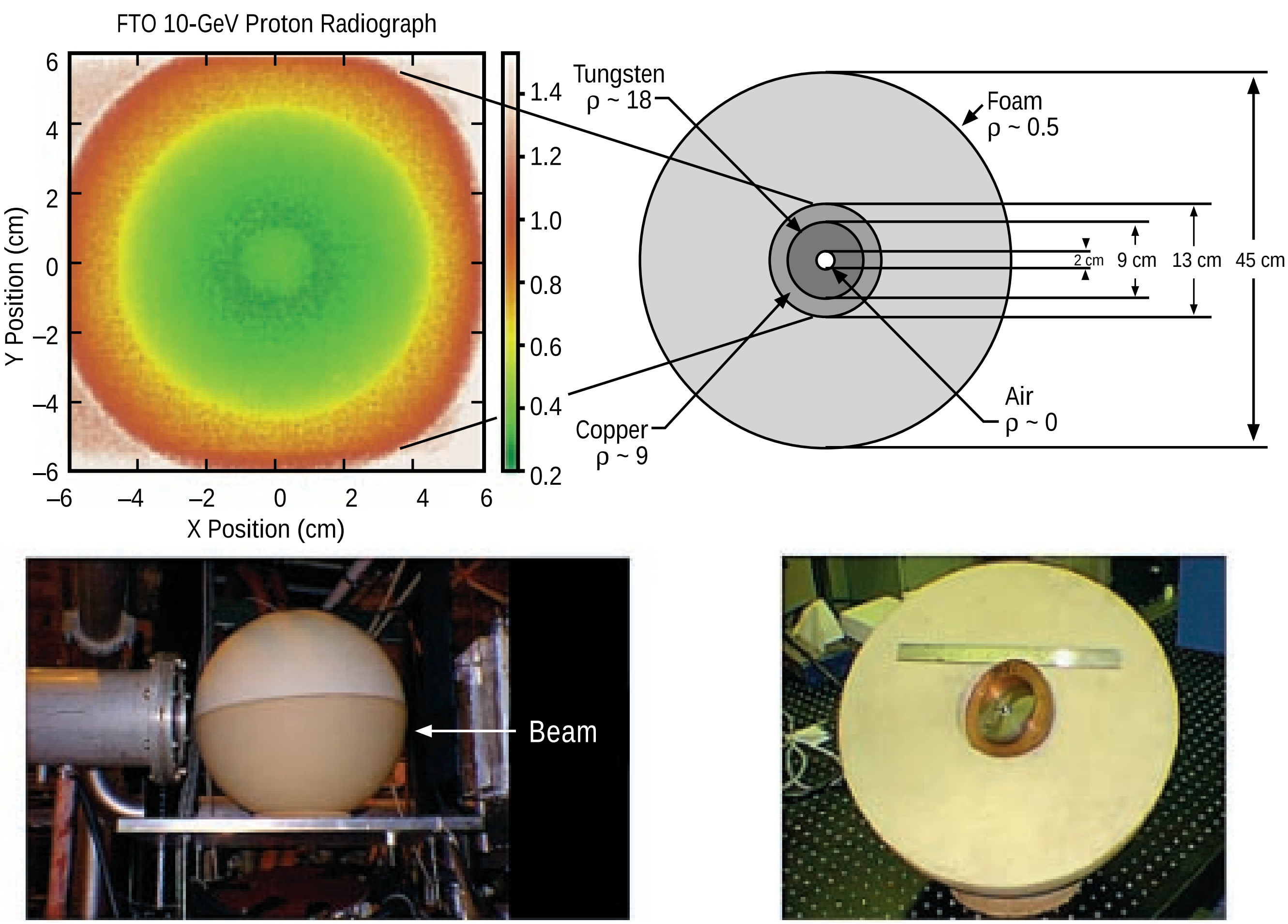


Fig. II-58. Proton radiograph of the French Test Object using 10-GeV protons from the AGS at BNL.